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Metathesis catalysts

Background of the Invention

Field of the Invention: The invention relates to polymeric transition metal catalysts, 5 to processes for preparing them, to intermediates and also to the use of the transition metal catalysts as catalysts in organic reactions, in particular in olefin metathesis reactions.

Brief Description of the Prior Art: Olefin metathesis reactions, for example ring-10 closing metathesis (RCM), cross-metathesis (CM) and ring-opening metathesis polymerizations (ROMP), are important synthetic methods for forming C-C bonds.

For olefin metathesis reactions, a multiplicity of catalyst systems has been developed, which are described in summary, for example, in T. M. Trnka, R. H. 15 Grubbs, *Acc. Chem. Res.* **2001**, 34, 18-29.

With regard to activity, those catalyst systems which comprise alkoxybenzylidene 20 complexes of transition metals in particular have proven useful. However, the removal and, if possible, the reuse of catalysts is becoming more important, since catalyst metal residues in the product may considerably impair its quality.

For example, Veldhuizen et al., *J. Am. Chem. Soc.* **2002**, 124, 4954-4955 disclose 25 phosphine-alkoxybenzylidene complexes of ruthenium which are suitable as reusable catalysts for the cross-metathesis of tricyclic norbornenes. However, this restriction to specific substrates is a hindrance to industrial use.

Gessler et al., *Tetrahedron Lett.* **41**, **2000**, 9973-9976 also describe stable ruthenium 30 complexes which contain dihydroimidazol-2-ylidene and isopropoxybenzylidene ligands. However, the difficult recovery of the catalyst is not satisfactory for industrial applications.

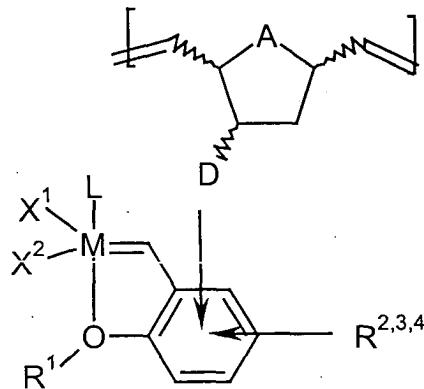
WO 02/14376 A2 describes dendrimeric ruthenium complexes which have dihydroimidazol-2-ylidene and isopropoxybenzylidene ligands and can advantageously be removed from the reaction products in the catalytic reaction mixtures which result from olefin metathesis reactions. However, a disadvantage of these catalysts is the complicated synthesis of the dendritic framework.

There was therefore still a need for easily obtainable catalysts which have high activity even on reuse and can easily be removed from the catalytic reaction mixtures.

Summary of the Invention

Surprisingly, polymeric compounds have now been found which contain at least

15 • structural units of the formula (Ia),



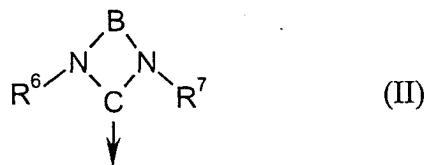
where

20

M is a transition metal of the 8th transition group of the Periodic Table,

X¹ and X² are the same or different and are each chlorine, bromine or iodine,

L is an N-heterocyclic carbene ligand of the formula (II)



5 where the direction of the arrow is intended to represent the bond to M and where

10 B is a 1,2-ethanediyl or 1,2-ethenediyl radical which is optionally mono- or disubstituted by C₁-C₄-alkyl, C₆-C₁₅-arylalkyl or C₅-C₁₄-aryl and

R⁶ and R⁷ are each independently C₁-C₂₀-alkyl or C₅-C₂₄-aryl,

15 R¹ is cyclic, straight-chain or branched C₁-C₂₀-alkyl or C₅-C₂₄-aryl and

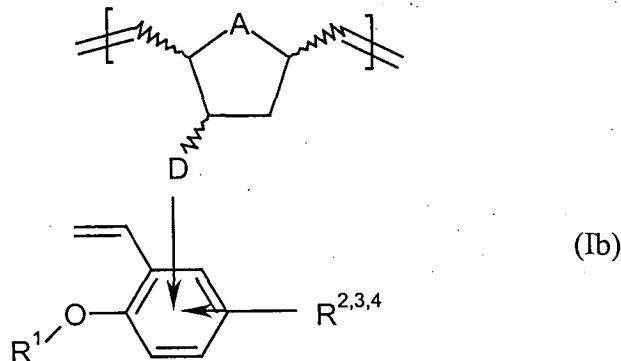
R², R³ and R⁴ are each independently hydrogen, C₁-C₂₀-alkyl, C₅-C₂₄-aryl, halogen, C₁-C₄-fluoroalkyl, C₁-C₄-alkoxy, C₅-C₁₄-aryloxy, (C₁-C₈-alkyl)OCO-, (C₁-C₈-alkyl)CO₂-, (C₅-C₁₄-aryl)OCO- or (C₅-C₁₄-aryl)CO₂- and/or

20 in each case two radicals in an ortho-arrangement to one another from the group of R², R³ and R⁴ are part of a cyclic system which consists of a carbon framework having 5 to 22 carbon atoms, one or more carbon atoms of the cyclic system optionally being replaced by heteroatoms from the group of sulphur, oxygen or nitrogen, and the cyclic system also being optionally mono- or polysubstituted by radicals selected from the group of halogen, C₁-C₄-fluoroalkyl, (C₁-C₄-alkyl)OCO-, (C₁-C₈-alkyl)CO₂-, (C₆-C₁₀-aryl)OCO- or (C₅-C₁₄-aryl)CO₂- and

A is oxygen, sulphur, sulphonyl, sulphonyl or CR^8R^9 where R^8 and R^9 are each independently hydrogen or $\text{C}_1\text{-C}_4$ -alkyl and

5 D is $\text{C}_1\text{-C}_8$ -alkylene, $[(\text{C}_1\text{-C}_8\text{-alkylene})\text{-O-}]_n$ where $n = 1$ to 12, $(\text{C}_1\text{-C}_8\text{-alkylene})\text{CO}_2$ -, $(\text{C}_1\text{-C}_8\text{-alkylene})\text{-OCO-}(\text{C}_1\text{-C}_8\text{-alkylene})$, $(\text{C}_1\text{-C}_8\text{-alkylene})\text{CO}_2\text{-}(\text{C}_1\text{-C}_8\text{-alkylene})$, $(\text{C}_1\text{-C}_8\text{-alkylene})\text{CONR}^{10}$ -, $(\text{C}_1\text{-C}_8\text{-alkylene})\text{NR}^{10}\text{CO-}$, $(\text{C}_1\text{-C}_8\text{-alkylene})\text{CONR}^{10}\text{-}(\text{C}_1\text{-C}_8\text{-alkylene})$ or $(\text{C}_1\text{-C}_8\text{-alkylene})\text{NR}^{10}\text{CO-}(\text{C}_1\text{-C}_8\text{-alkylene})$ where R^{10} is 10 hydrogen or $\text{C}_1\text{-C}_4$ -alkyl

- and structural units of the formula (Ib)

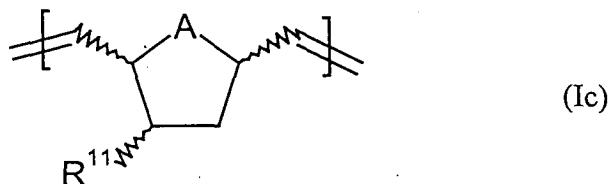


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where A, D, R^1 , R^2 , R^3 and R^4 each independently have the same definitions and fulfil the same conditions as specified under the formula (Ia) and

- optionally structural units of the formula (Ic)

20



where

5 A has the same definition and fulfils the same conditions as specified under formula (Ia) and

10 R¹¹ is C₁-C₈-alkyl, [(C₁-C₈-alkylene)-O-]_n-(C₁-C₈-alkyl) where n = 1 to (C₁-C₈-alkylene)CO₂-(C₁-C₈-alkyl), (C₁-C₈-alkylene)-OCO-(C₁-C₈-alkyl), (C₁-C₈-alkylene)-OCO-(C₅-C₁₄-aryl), (C₁-C₈-alkylene)CO₂-(C₅-C₁₄-aryl), (C₁-C₈-alkylene)CONR¹⁰-(C₁-C₈-alkyl), (C₁-C₈-alkylene)NR¹⁰CO-(C₁-C₈-alkyl), (C₁-C₈-alkylene)-CONR¹⁰-(C₅-C₁₄-aryl) or (C₁-C₈-alkylene)NR¹⁰CO-(C₅-C₁₄-aryl) where R¹⁰ is hydrogen or C₁-C₄-alkyl.

15 Detailed Description of the Invention

Within the scope of the invention, all radical definitions and illustrations listed in general or within areas of preference may be combined with each other, i.e. the particular areas and areas of preference may also be combined as desired.

20 Wavy lines in formulae are intended to emphasize that in each case both possible isomers are intended to be encompassed by the representation.

25 For the purposes of the invention, alkyl, alkylene and alkoxy each independently represent a straight-chain, cyclic, branched or unbranched alkyl, alkylene and alkoxy radical respectively, each of which may optionally be further substituted by C₁-C₄-alkoxy radicals. The same applies to the alkyl moiety of an arylalkyl radical.

In all contexts, C₁-C₄-alkyl is preferably, for example, methyl, ethyl, n-propyl, isopropyl, n-butyl and tert-butyl, C₁-C₈-alkyl is additionally neopentyl, n-pentyl,

cyclohexyl, n-hexyl, n-heptyl, n-octyl and isooctyl, and C₁-C₂₀-alkyl is further additionally, for example, n-decyl, n-dodecyl, n-hexadecyl and n-octadecyl.

5 In all contexts, C₁-C₄-alkylene is preferably, for example, methylene, 1,1-ethylene, 1,2-ethylene, 1,1-propylene, 1,2-propylene, 1,3-propylene, 1,1-butylene, 1,2-butylene, 2,3-butylene and 1,4-butylene, and C₁-C₈-alkylene is additionally 1,5-pentylene, 1,6-hexylene, 1,1-cyclohexylene, 1,4-cyclohexylene, 1,2-cyclohexylene and 1,8-octylene.

10 For the purposes of the invention, aryl is a carbocyclic radical or heteroaromatic radical in which no, one, two or three framework atoms per cycle, although at least one framework atom in the entire radical, is a heteroatom which is selected from the group of nitrogen, sulphur and oxygen. The carbocyclic aromatic radicals or heteroaromatic radicals may also be substituted by up to five identical or different substituents per cycle, selected, for example, from the group of hydroxyl, chlorine, 15 fluorine, nitro and C₁-C₁₂-alkyl. For the purposes of the invention, aryl is preferably an above-defined carbocyclic radical.

The same applies to the aryl moiety of an arylalkyl radical. C₆-C₁₅-arylalkyl is, for example, and with preference, benzyl.

20 For the purposes of the invention, fluoroalkyl is in each case independently a straight-chain, cyclic, branched or unbranched alkyl radical which may be singly, multiply or fully substituted by fluorine atoms.

25 For example and with preference, C₁-C₄-fluoroalkyl is in all contexts preferably trifluoromethyl, 2,2,2-trifluoroethyl, pentafluoroethyl and nonafluorobutyl.

30 The polymeric compounds containing at least the structural units of the formula (Ia) and (Ib) and optionally (Ic) may also contain structural units which are derived from olefins which are suitable for ring-opening metathesis polymerization. These are

sufficiently well known from the literature (e.g. from T. M. Trnka, R. H. Grubbs, *Acc. Chem. Res.* **2001**, *34*, 18-29 and the literature cited there).

5 Polymeric compounds containing structural units of the formulae (Ia) and (Ib) and optionally structural units of the formulae (Ic) are preferably those which have a degree of polymerization (numerical average) of 6 to 2000, particularly preferably 10 to 500.

10 It is pointed out that the scope of the invention also encompasses polymeric compounds in which the structural units of the formulae (Ia) and/or of the formulae (Ib) and/or optionally the structural units of the formulae (Ic) may in each case have different definitions for A and D or M, L, X¹, X² or R¹, R², R³, R⁴ or R¹¹, although preference is given to those polymeric compounds in which M, L, X¹ and X² in the structural units of the formula (Ia), and likewise R¹, R², R³ and R⁴ in the structural 15 units of the formula (Ia) and (Ib), and R¹¹ in any structural units of the formula (Ic) present and likewise A and D in the structural units of the formula (Ia) and (Ib) and any structural units of the formula (Ic) present are in each case identical.

20 Preference is further given to those polymeric compounds in which the proportion of the structural units of the formula (Ia) and of the formula (Ib) and any structural units of the formula (Ic) present (average proportion by weight) is 80% or more, preferably 90% or more and particularly preferably 98% or more.

25 The ratio of structural units of the formula (Ia) to structural units of the formula (Ib) in the polymer is preferably 1:2 to 1:500, particularly preferably 1:8 to 1:200.

30 When the polymeric compound also contains structural units of the formula (Ic), the ratio of structural units of the formula (Ia) to structural units of the formula (Ic) is in addition preferably 10:1 to 1:200, particularly preferably 1:1 to 1:100 and very particularly preferably 1:10 to 1:50.

D in the structural units (Ia) and (Ib) is preferably bonded via the ortho-position to the olefin or to the ylidene unit.

5 M in formula (Ia) is preferably ruthenium or osmium, particularly preferably ruthenium.

X¹ and X² are preferably identical and are each chlorine or bromine, particularly preferably chlorine.

10

L in formula (Ia) is an N-heterocyclic carbene ligand of the formula (II).

B in formula (II) is preferably 1,2-ethanediyl or 1,2-ethenediyl.

15 R⁶ and R⁷ in formula (II) are preferably and in each case independently, although preferably identically, a primary C₅-C₂₀-alkyl radical, with the proviso that the carbon atom bonded to the nitrogen atom bears a tertiary alkyl radical, or are each a secondary C₃-C₂₀-alkyl radical, a tertiary C₄-C₂₀-alkyl radical or a phenyl radical which is further mono- or polysubstituted, although at least in an ortho-position, by
20 C₁-C₄-alkyl radicals.

25 R⁶ and R⁷ in the formula (III) are particularly preferably identical and are each isopropyl, sec-butyl, tert-butyl, 1-methylbutyl, 1-ethylpropyl, 1,1-dimethylpropyl, 1,2-dimethylpropyl, 1-methylpentyl, 1,1-dimethylbutyl, 1,2-dimethylbutyl, 1,3-dimethylbutyl, 1-ethylbutyl, 1,1,2-trimethylpropyl, 1,2,2-trimethylpropyl, 1-ethyl-1-methylpropyl, cyclopentyl, cyclohexyl, cycloheptyl, neopentyl, adamantyl, norbornyl, o-tolyl, 2,6-dimethylphenyl, 2-ethyl-6-methylphenyl, 2,6-diisopropylphenyl, o-anisyl, 2,6-dimethoxyphenyl, mesityl and isityl.

1 R¹ is preferably a radical which is selected from the group of ethyl, isopropyl, tert-butyl, neopentyl, cyclohexyl and cyclopentyl, and even greater preference is given to isopropyl.

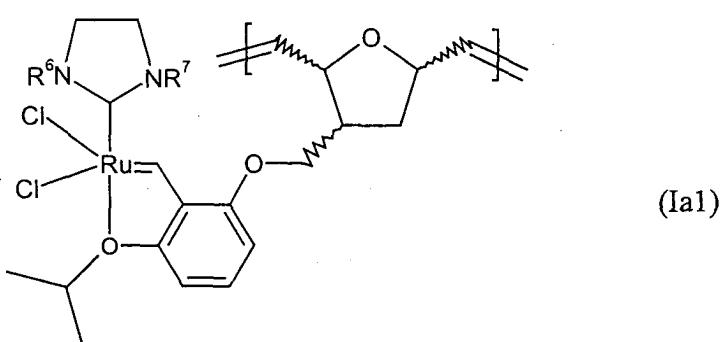
5 5 R², R³ and R⁴ are preferably each independently hydrogen, C₁-C₄-alkyl, fluorine, chlorine or C₁-C₄-fluoroalkyl, and are particularly preferably identical and are each hydrogen.

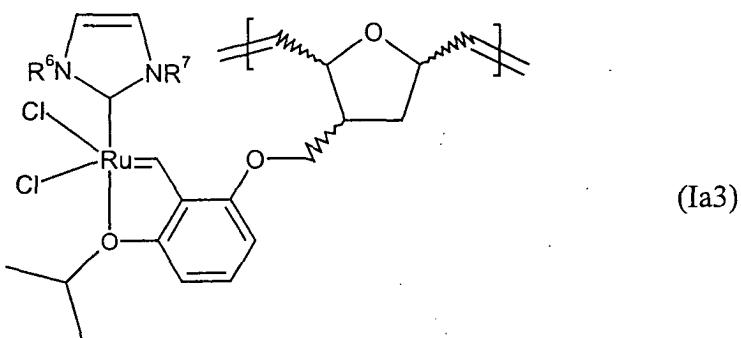
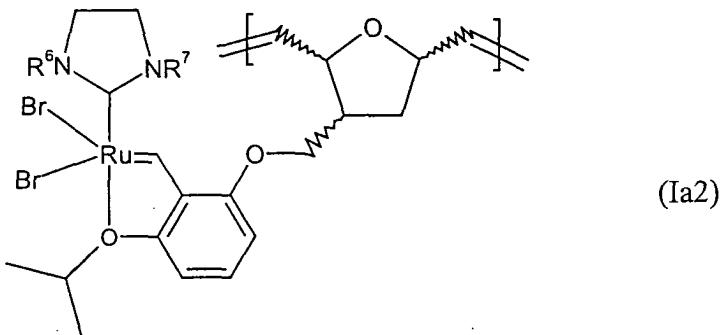
10 A 10 is preferably oxygen or CH₂, and even greater preference is given to oxygen.

D 15 is preferably [(C₁-C₄-alkylene)-O-]_n where n = 1 or 2, or (C₁-C₄-alkylene)-CO₂-, particularly preferably (C₁-C₄-alkylene)-O- and very particularly preferably CH₂O.

15 R¹¹ 20 is preferably (C₁-C₄-alkylene)-O-]_n-(C₁-C₄-alkyl) where n = 1 or 2, (C₁-C₄-alkylene)CO₂-(C₁-C₄-alkyl) or (C₁-C₄-alkylene)CO₂-(C₅-C₁₄-aryl), particularly preferably CH₂O₂C-(C₁-C₄-alkyl) or CH₂OCO-(C₅-C₁₄-aryl), and very particularly preferably CH₂OCOPhenyl or CH₂OCO(o-methylaminophenyl), which may be used as a fluorescence marker.

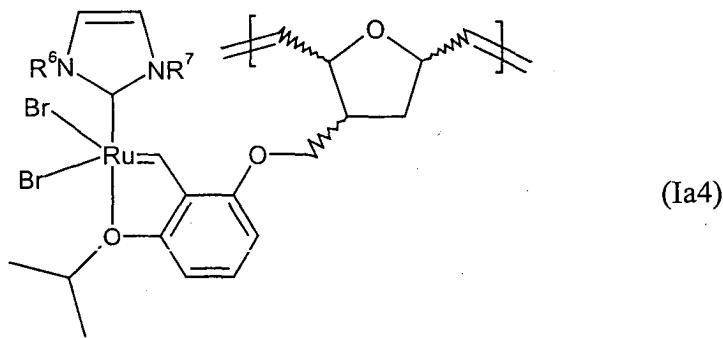
Very particularly preferably, the polymeric compounds according to the invention contain structural units of the formula (Ia):





or

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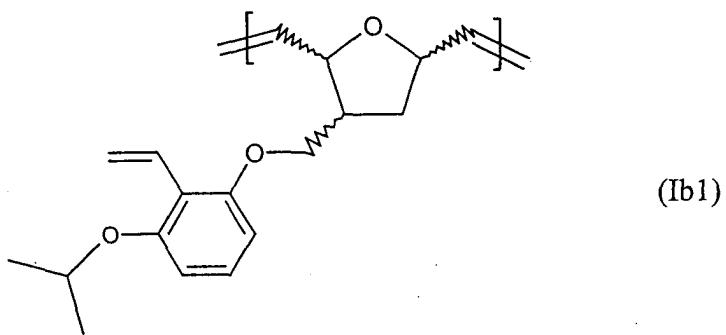


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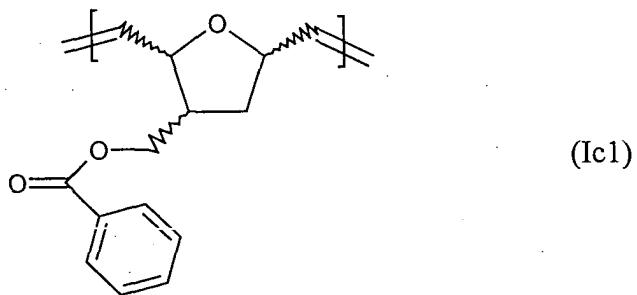
where R^6 and R^7 are identical and are each isopropyl, sec-butyl, tert-butyl, 1-methylbutyl, 1-ethylpropyl, 1,1-dimethylpropyl, 1,2-dimethylpropyl, 1-methylpentyl, 1,1-dimethylbutyl, 1,2-dimethylbutyl, 1,3-dimethylbutyl, 1-ethylbutyl, 1,1,2-trimethylpropyl, 1,2,2-trimethylpropyl, 1-ethyl-1-methylpropyl, cyclopentyl-, cyclohexyl-, cycloheptyl-, neopentyl, adamanyl, norbornyl, o-tolyl, 2,6-

dimethylphenyl, 2-ethyl-6-methylphenyl, 2,6-diisopropylphenyl, 2,6-dimethoxyphenyl and mesityl.

Very particularly preferably, the polymeric compounds according to the invention
5 contain as structural units of the formula (Ib):

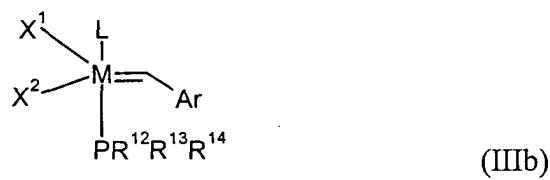
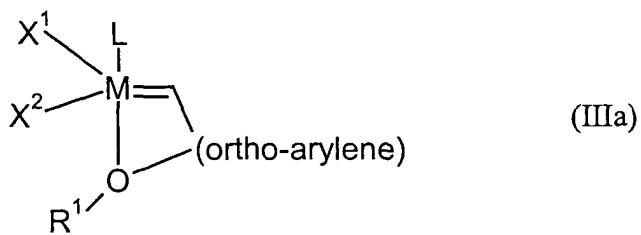


When the polymeric compounds according to the invention contain structural units of
10 the formula (Ic), very particular preference is given to the following:



The polymeric compounds according to the invention containing structural units of
15 the formulae (Ia) and (Ib) and optionally (Ic) are accessible by a process which is
likewise encompassed by the invention.

This is a process for preparing polymeric catalysts, which is characterized in that
compounds of the formula (IIIa) and/or (IIIb)



5 where

R¹, L, X¹ and X² each have the definition and areas of preference specified under formula (Ia) and

10 ortho-arylene is an ortho-phenylene or ortho-naphthylene radical, for example 1,2-naphthylene, and the radicals mentioned may also be substituted by one, two, three or four radicals per cycle which are selected from the group of C₁-C₄-alkyl, C₅-C₁₄-aryl and C₁-C₄-alkoxy and

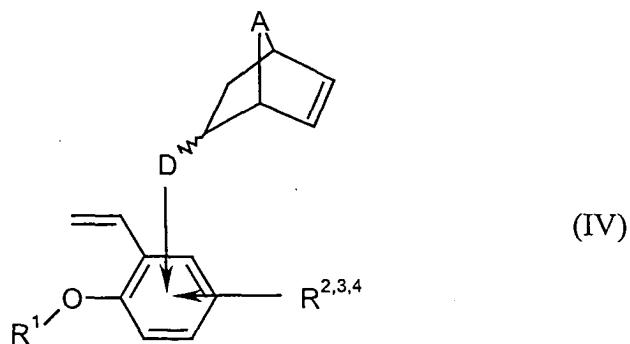
15 Ar is C₅-C₁₄-aryl and

R¹², R¹³ and R¹⁴ are each independently C₁-C₈-alkyl or C₅-C₁₄-aryl

are reacted

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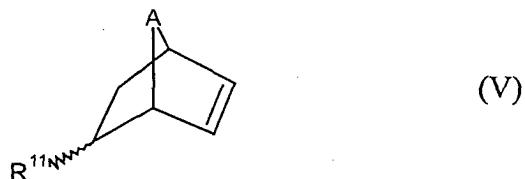
- with at least one compound of the formula (IV)



where

5 R¹, R², R³, R⁴, A and D have the definition and areas of preference specified under formula (Ia).

- and optionally with at least one compound of the formula (V)



10

where

15 R¹¹ and A each have the definition and areas of preference specified under formula (Ic)

- and optionally with one or more further olefins which can be polymerized by ring-opening metathesis.

20 The compounds of the formula (IV) are hitherto unknown and therefore likewise encompassed by the invention.

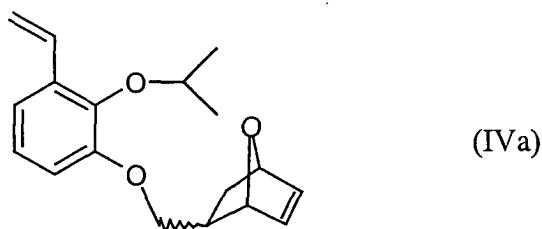
In formula (IIIa), ortho-arylene is preferably ortho-phenylene.

In formula (IIIb), aryl is preferably phenyl.

5 Also, R¹², R¹³ and R¹⁴ in formula (IIIb) are preferably identical and each C₁-C₈-alkyl or C₅-C₁₄-aryl, particularly preferably identical and each cyclohexyl.

A particularly preferred compound of the formula (IV) is (7-oxa-2-norborn-2-en-5-yl-methyl) (2-isopropoxy-3-ethenylphenyl) ether (IVa).

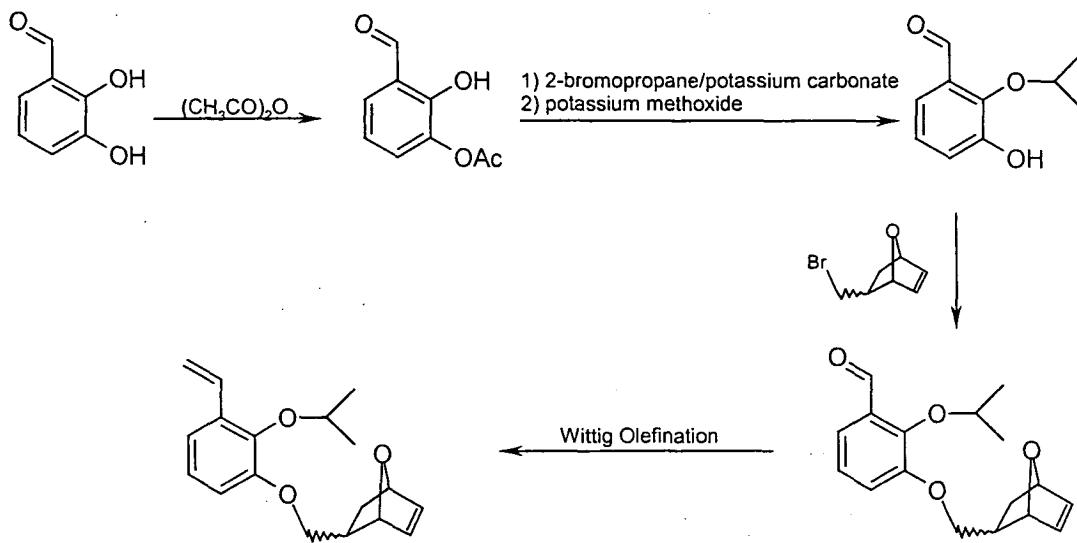
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15 The compounds of the formula (IIIa) and (IIIb) are known from the literature or can be prepared in a similar manner to methods known from the literature (see in particular Veldhuizen et al., *J. Am. Chem. Soc.* **2002**, *124*, 4954-4955).

The compounds of the formulae (IV) and (V) may be prepared in a similar manner to the literature methods. As an example, the synthetic sequence for the compound of the formula (IVa) is given.

20



Preference is given to carrying out the process according to the invention in an organic solvent. Examples of useful organic solvents include amides, for example 5 dimethylformamide; N-methylpyrrolidinone, halogenated aliphatic or optionally halogenated, aromatic solvents having up to 16 carbon atoms, e.g. toluene, o-, m-, p- xylene, chloroform, dichloromethane, chlorobenzene, the isomeric dichlorobenzenes, fluorobenzene, nitriles, e.g. acetonitrile and benzonitrile, sulphoxides such as dimethyl sulphoxide or mixtures thereof.

10

Preferred organic solvents are toluene and dichloromethane.

The reaction temperature may be, for example -30°C to 100°C, preferably 10 to 40°C.

15

The reaction time may be, for example, 2 minutes to 24 hours, preferably 5 min to 1 h.

When using compounds of the formula (IIIb), it is advantageous also to use 20 compounds which are capable of scavenging phosphines. These are preferably

copper salts, in particular CuCl_2 and CuCl which are also preferably used in an equimolar amount or in a molar excess.

5 Depending on the choice of the molar ratios of the monomeric compounds (IIIa) and/or (IIIb), (IV) and any (V), a corresponding average molar composition is achieved in the polymeric compounds according to the invention. The areas of preference specified above for the ratios of the structural units of the formulae (Ia), (Ib) and any (Ic) consequently apply correspondingly to the preferred ranges of the ratios of monomeric compounds to be used.

10

The workup can be effected in such a way, for example, that any insoluble constituents present are filtered out and the filtrate is concentrated, the residue is subsequently washed with organic solvent and then optionally dried under reduced pressure.

15

In this way, the polymeric compounds according to the invention comprising the structural units of the formulae (Ia) and (Ib) and any (Ic) can be obtained in high yields. These polymeric compounds according to the invention are suitable, for example, as metathesis catalysts, in particular for ring-closing metatheses, ring-20 opening metatheses, cross-metatheses and ring-opening metathesis polymerizations.

25

The invention therefore also encompasses a process for preparing olefins by catalytic olefin metathesis, which is characterized in that the catalysts used are the polymeric compounds according to the invention containing the structural units of the formulae (Ia) and (Ib) and optionally (Ic).

An example of a possible procedure is to react the reactant olefin, optionally in an organic solvent, with the polymeric compounds according to the invention and in this way to obtain catalytic reaction mixtures which contain the product.

30

The reaction temperature may be, for example, -30 to 100°C.

5 In a preferred embodiment, the polymeric compounds according to the invention are removed from the catalytic reaction mixtures and reused for the preparation of olefins by catalytic olefin metathesis. The procedures of removal and reuse can be repeated once or more than once.

10 In a further preferred embodiment of the process according to the invention, the removal can be effected in such a way that sufficient aliphatic hydrocarbons, preferably having 5 to 12 carbon atoms, and/or diethyl ether are added to the catalytic reaction mixtures to at least partially precipitate out the polymeric compounds. Subsequently, the polymeric compounds according to the invention can be removed by filtration and/or decanting from the product solution.

15 Aliphatic hydrocarbons having 5 to 12 carbon atoms are, for example and with preference, n-pentane and n-hexane.

20 The polymeric compounds according to the invention are suitable in particular as catalysts, preferably as catalysts in metathesis reactions, for example cross-metatheses, ring-closing metatheses and ring-opening metathesis polymerizations, optionally with subsequent cross-metathesis.

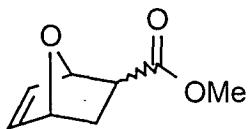
25 They are notable for their high activities for a multiplicity of different substrates, for example ring-closing metatheses at low catalyst loading result in quantitative conversions even in a short time and at low temperatures.

The polymeric compounds according to the invention can also be removed easily and in high yields from the catalytic reaction mixtures and only have a small loss of activity on reuse.

Examples

Example 1

5 Preparation of methyl 7-oxanorborn-2-en-5-ylcarbonate



Furan and methyl acrylate were distilled before use.

10

A mixture of furan (22.6 ml, 311 mmol) and methyl acrylate (20.0 ml, 222 mmol) was cooled to -20°C under nitrogen. AlCl_3 (8.880 g, 67 mmol) was added to this mixture in four portions, likewise under nitrogen. The reaction mixture was stirred for 30 min and subsequently allowed to heat to room temperature within 2 h. The 15 crude reaction mixture was admixed with ethyl acetate (30 ml) and filtered. The filtrate was washed with saturated NH_4Cl solution (50 ml) and dried over magnesium sulphate and concentrated under reduced pressure.

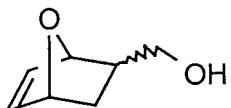
20 The crude product was purified by flash chromatography (using 50 : 50 cyclohexane : ethyl acetate as the eluent) to obtain the pure product 16.2 g (55% of theory) as a 55 : 45 mixture of the exo- and endo-isomers.

25 δ_{H} (200 MHz, CDCl_3 , E1 = *exo*-isomer, E2 = *endo*-isomer): 6.40-6.46 (1H, m, H-5 E2), 6.32-6.40 (2H, m, H-5,6 E1), 6.22 (1H, dd, J 2, 15 Hz, H-6 E2), 5.12-5.20 (2H, m, H-1,4 E2), 4.98-5.08 (2H, m, H-1,4 E1), 3.72 (3H, s, CH_3 E1), 3.62 (3H, s, CH_3 E2), 3.10 (1H, quint., J 6 Hz, H-3 E1), 2.42 (1H, dd, J 3, 8 Hz, H-3 E1), 2.04-2.22 (1H, m, H-2 E1), 1.48-1.70 (2H, m, H-3 E2), 1.20-1.30 (1H, t, 6 Hz, H-2 E2).

Example 2

Preparation of 7-oxanorborn-2-en-5-ylmethanol

5



A solution of methyl 7-oxanorborn-2-en-5-ylcarbonate (16.163 g, 105 mmol, see Example 1) in THF (75 ml) was added dropwise with stirring and under nitrogen to a suspension of lithium aluminium hydride (4.376 g, 115 mmol) in anhydrous THF (100 ml), in such a way that the solution boiled gently. The reaction mixture was subsequently stirred at room temperature for another 12 h and then quenched by cautiously adding an ice-water mixture. The organic phase was removed and the aqueous phase extracted with ethyl acetate (3 x 200 ml). The combined organic phases were washed with water (600 ml) and saturated sodium chloride solution (600 ml), dried over sodium sulphate and concentrated under reduced pressure.

The crude product was purified by flash chromatography (using a 50 : 50 mixture of cyclohexane and ethyl acetate). 3.7 g (32% of theory) of the pure product were obtained.

20

δ_H (500 MHz, $CDCl_3$, E1 = *exo*-isomer, E2 = *endo*-isomer): 6.38 (1H, dd, J 1.5, 5.9 Hz, H-5 E2), 6.32 (2H, br s, H-5,6 E1), 6.28 (1H, dd, J 1.0, 5.9 Hz, H-6 E2), 5.01 (1H, d, J 3.7 Hz, H-1 E2), 4.93 (2H, m, H-1,4 E1), 4.87 (1H, s, H-4 E2), 3.75 (1H, dd, J 5.1, 10.4 Hz, HCHOH E2), 3.52-3.59 (2H, m, CH₂OH E1), 3.19 (1H, t, J 10.1 Hz, HCHOH E2), 2.44 (1H, m, H-2 E2), 1.97-2.00 (1H, m, H-3 E2), 1.76-1.81 (1H, m, H-2 E1), 1.34-1.39 (2H, m, H-3 E1), 0.70 (1H, dd, J 4.1, 11.3 Hz, H-3 E2).

Example 3

Preparation of 7-oxanorborn-2-en-5-yl-methyl bromide

5

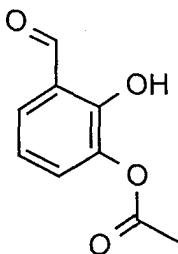


Tetrabromomethane (1.161 g, 3.50 mmol) was added to a solution of 7-oxanorborn-2-en-5-ylmethanol (0.305 g, 2.50 mmol, from Example 2) in CH_2Cl_2 (12.5 ml). The solution was cooled to 0°C and admixed with triphenylphosphine (1.836 g, 7 mmol).
10 The reaction mixture was allowed to warm to room temperature and stirred for 12 h. The solvent was removed under reduced pressure and the remaining solid was taken up in cyclohexane. The crude product was purified by flash chromatography (using a 98 : 2 mixture of cyclohexane and ethyl acetate). 0.3 g (59% of theory) of the pure product were obtained. The product was stored under cool conditions with the exclusion of light.
15

δ_{H} (200 MHz, CDCl_3 , E1 = *exo*-isomer, E2 = *endo*-isomer): 6.46 (1H, dd, J 2, 6 Hz, H-5 E2), 6.35 (2H, br s, H-5,6 E1), 6.36 (1H, dd, J 2, 8 Hz, H-6 E2), 4.96-5.08 (2H, m, H-1,4 E2), 4.99 (1H, d, J 4 Hz, H-1 E1), 4.86 (1H, s, H-4 E1), 3.42-3.49 (2H, m, CH_2Br E1), 3.36 (1H, dd, J 7, 10 Hz, $\underline{\text{HCHBr}}$ E2), 3.19 (1H, t, J 10 Hz, $\underline{\text{HCHBr}}$ E2),
20 2.58-2.68 (1H, m, H-2 E2), 2.06-2.12 (1H, m, H-3 E2), 2.00-2.06 (1H, m, H-2 E1), 1.37-1.43 (1H, m, H-3 E1), 1.36 (1H, dt, J 4, 12 Hz, H-3 E1), 0.80 (1H, dd, J 4, 12 Hz, H-3 E2).

Example 4

Preparation of 2-hydroxy-3-acetoxybenzaldehyde



5

A solution of 2,3-dihydroxybenzaldehyde (4.000 g, 28.96 mmol) and acetic anhydride (3.260 g, 32.00 mmol) in acetic acid (40 ml) was heated to reflux under a nitrogen atmosphere for 72 h.

10

After cooling, the reaction mixture was poured into ice-water, and a white solid precipitated out.

15

After extraction with CH_2Cl_2 (2 x 100 ml), the combined organic phases were rapidly washed with ice-cold water (2 x 100 ml) and saturated sodium chloride solution (100 ml). After drying over magnesium sulphate and concentrating to a volume of approx. 70 ml, hexane (50 ml) was added and the mixture was concentrated again under reduced pressure until the commencement of crystallization. The mixture was aerated and cooled to 0°C. After one hour at 0°C, the precipitated solid was filtered off with suction and dried under high vacuum.

20

3.95 g (76 % of theory) of 2-hydroxy-3-acetoxybenzaldehyde were obtained as a colourless crystalline solid.

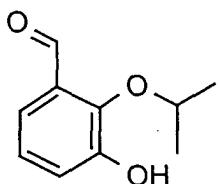
25

δ_{H} (500 MHz, CDCl_3): 11.12 (1H, s, CHO), 9.92 (1H, s, OH), 7.49 (1H, dd, J 1.5, 7.7 Hz), 7.32 (1H, dd, J 0.7, 7.9 Hz), 7.03 (1H, dd, J 7.7, 7.9 Hz), 2.86 (3H, s, OCOMe).

Example 5

Preparation of 2-isopropoxy-3-hydroxybenzaldehyde

5



A 100 ml round-bottomed flask was charged with dried molecular sieve 4 A mol (approx. 1 g) and dried (130°C, 12 h) K₂CO₃ (5.520 g, 40.00 mmol) and charged 10 under a nitrogen atmosphere with a solution of 2-hydroxy-3-acetoxybenzaldehyde (3.600 g, 19.98 mmol, from Example 3) in dried DMF (50 ml). After stirring for 30 minutes, 2-bromopropane (13.00 ml, 138.88 mmol) was added via a cannula and the resulting yellow solution was heated to 50°C for 12 h. After cooling to room temperature, water (100 ml) was added. The biphasic mixture was extracted with 15 diethyl ether (3 x 200 ml). The combined organic phases were washed with water (5 x 100 ml), dried over magnesium sulphate and concentrated under reduced pressure.

¹H NMR analysis showed a 92:8 mixture of mono- and bis-alkylated products. To 20 hydrolyse the 3-acetoxy group, the residue was taken up in methanol (20 ml) and admixed with a 30% solution of sodium methoxide in methanol until the resulting yellow solution gained no more colour intensity on further addition.

The methanolic solution was concentrated under reduced pressure to dryness and the 25 remaining residue was taken up in water (40 ml). The yellow solution of the phenoxide was extracted with MTBE (2 x 20 ml), in order to remove the undesired bis-alkylated by-product. Subsequently, acetic acid was added to the aqueous phase until decolorization.

Subsequently, extraction was effected using MTBE (5 x 50 ml), and the combined organic phases were dried over magnesium sulphate and concentrated under reduced pressure. The yellow residue was purified by column chromatography (eluent CH_2Cl_2). 2.66 g (74% of theory) of the product were obtained as a colourless solid.

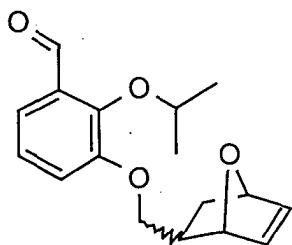
5

δ_{H} (500 MHz, CDCl_3): 10.25 (1H, s, CHO), 7.37 (1H, dd, J 1.4, 7.7 Hz), 7.20 (1H, dd, J 1.4, 7.9 Hz), 7.11 (1H, dd, 7.7, 7.9 Hz), 5.96 (1H, s, OH), 4.33 (1H, septet, J 6.1 Hz $\text{CH}(\text{CH}_3)_2$), 1.38 (6H, d, J 6.1 Hz, $\text{CH}(\text{CH}_3)_2$).

10

Example 6

Preparation of 7-oxa-2-norborn-2-en-5-ylmethyl 2-isopropoxy-3-formylphenyl ether



15

7-Oxanorborn-2-en-5-ylmethyl bromide (1.0 g, 5.3 mmol from Example 3) and potassium carbonate (0.498 g, 3.6 mmol) were added to a solution of 2-isopropoxy-3-hydroxybenzaldehyde (0.317 g, 1.8 mmol from Example 5) in dry DMF (6 ml) and the reaction mixture was stirred at 50 to 60°C for 12h. After cooling to room temperature, water (10 ml) was added. The resulting biphasic mixture was extracted with MTBE (3 x 20 ml). The combined organic phases were washed with water (5 x 30 ml) and sodium hydrogencarbonate solution (30 ml), dried over magnesium sulphate and concentrated under reduced pressure. The crude product was purified by flash chromatography (eluent CH_2Cl_2). 0.4 g (76% of theory) of the pure product was obtained.

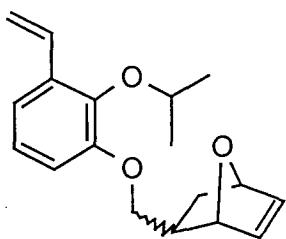
δ_H (500 MHz, $CDCl_3$, E1 = exo-isomer, E2 = endo-isomer): 10.45 (1H, s, CHO), 7.42 (1H, dd, J 1.9, 7.5 Hz, ArH), 7.02-7.14 (2H, m, ArH), 6.45 (1H, dd, J 1.6, 5.9 Hz, H-6 E2), 6.38 (2H, ddd, J 1.5, 5.9, 13.1 Hz, H-5,6 E1), 6.31 (1H, dd, J 1.3, 5.8 Hz, H-5 E2), 5.13 (2H, d, J 4.2 Hz, H-1 E2), 5.01 (2H, d, J 3.3 Hz, H-4 E2), 4.96-5.01 (2H, m, H-4,1 E1), 4.62-4.68 (1H, m, $CH(CH_3)_2$), 4.00-4.04 (2H, m, CH_2O E1), 3.93 (1H, dd, J 6.4, 9.1 Hz, $HCHO$ E2), 3.54 (1H, t, J 9.1 Hz, $HCHO$ E2), 2.76-2.81 (1H, m, H-2 E2), 2.10-2.15 (2H, m, H-3 E1 & E2), 1.51-1.54 (1H, m, H-3 E1), 1.56 (1H, dd, J 8, 12 Hz, H-2 E1), 1.36 (6H, d, J 6.1 Hz, $CH(CH_3)_2$), 0.86 (1H, dd, J 4.1, 11.4 Hz; H-3 E2).

10

Example 7

Preparation of 7-oxa-2-norborn-2-en-5-ylmethyl 2-isopropoxy-3-ethenylphenyl ether

15



20

25

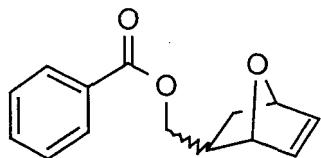
Potassium tert-butoxide (0.218 g, 1.94 mmol) was added at 0°C in one portion to a suspension of methyltriphenylphosphonium bromide (0.694 g, 1.94 mmol) in dry diethyl ether (5 ml) and the reaction mixture was stirred for 10 min. Subsequently, a solution of 7-oxa-2-norborn-2-en-5-ylmethyl 2-isopropoxy-3-formylphenyl ether (0.280 g, 0.97 mmol from Example 6) in diethyl ether (3.6 ml) was added and the mixture was stirred at 0°C for a further 20 min. Afterwards, the mixture was quenched by adding saturated ammonium chloride solution. The aqueous phase was extracted using diethyl ether (3 x 10 ml) and, after washing with water (30 ml) and saturated sodium chloride solution (30 ml), the combined organic phases were dried over magnesium sulphate and concentrated under reduced pressure.

The crude product was purified by flash chromatography (eluent CH_2Cl_2). 0.22 g (79% of theory) of the pure product was obtained.

5 δ_{H} (500 MHz, CDCl_3 , E1 = exo-isomer, E2 = endo-isomer): 7.09-7.15 (2H, m, ArH), 6.95-6.97 (1H, m, ArH), 6.73 (1H, d, J 8.0 Hz, ArCH), 6.43 (1H, dd, J 1.3, 5.8 Hz, H-6 E2), 6.36 (2H, s, H-5,6 E1), 6.27 (1H, dd, J 0.8, 5.8 Hz, H-5 E2), 5.71 (1H, d, J 17.8 Hz, HCH=CH), 5.26 (1H, dd, J 0.9, 11.1 Hz, HCH=CH), 5.15 (1H, d, J 3.7 Hz, H-1 E2), 4.97-4.99 (3H, m, H-4 E2 & H-4,1 E1), 4.45 (1H, septet, J 6.1 Hz, CH(CH₃)₂), 3.94-4.02 (2H, m, CH₂O E1), 3.91 (1H, dd, J 6.1, 9.1 Hz, HCHO E2), 3.49 (1H, t, J 9.1 Hz, HCHO E2), 2.75-2.81 (1H, m, H-2 E2), 2.08-2.13 (2H, m, H-3 E1 & E2), 1.50 (1H, dd, J 8.1, 11.5 Hz, H-3 E1), 1.56 (1H, dt, J 11.5, 3.9 Hz, H-2 E1), 1.32 (6H, d, J 6.1 Hz, CH(CH₃)₂), 0.84 (1H, dd, J 4.1, 11.4 Hz, H-3 E2).

15 Example 8

Preparation of 7-oxa-2-norborn-2-en-5-yl-methyl benzoate



20

A solution of benzoyl chloride (0.93 ml, 8 mmol) in CH_2Cl_2 (8 ml) was added dropwise at 0°C to a mixture of 7-oxanorborn-2-en-5-ylmethanol (0.505 g, 4.0 mmol from Example 2), 4-dimethylaminopyridine (0.049 g, 0.4 mmol) and triethylamine (2.2 ml, 16 mmol) in CH_2Cl_2 (8 ml). The reaction mixture was stirred at room temperature and the progress of the reaction was followed by thin-layer chromatography (eluent 80 : 20 ethyl acetate : cyclohexane). After 2.5 h, the reaction mixture was quenched by adding water (20 ml). The product was extracted using CH_2Cl_2 (3 x 20 ml). The combined organic phases were washed with dilute

hydrochloric acid, 10% NaHCO₃-solution (60 ml), water (60 ml) and concentrated sodium chloride solution (60 ml), dried over magnesium sulphate and concentrated under reduced pressure.

5 The crude product was purified by flash chromatography (eluent 70 : 30 to 90 : 10 CH₂Cl₂ : cyclohexane). 0.68 g (74% of theory) of the pure product was obtained.

10 δ_{H} (500 MHz, CDCl₃, E1 = exo-isomer, E2 = endo-isomer): 8.03-8.07 (2H, m, ArH), 7.55-7.57 (1H, m, ArH), 7.43-7.47 (2H, m, ArH), 6.41 (1H, dd, J 1.4, 5.8 Hz, H-5 E2), 6.33-6.36 (3H, m, H-5,6 E1 & H-6 E2), 5.06 (2H, d, J 3.7 Hz, H-1 E2), 4.98-5.01 (2H, m, H-1,4 E1), 4.92 (1H, s, H-4 E2), 4.48 (1H, dd, J 6.0, 10.8 Hz, HCHO E1), 4.27 (1H, dd, J 6.2, 11.1 Hz, HCHO E2), 3.87 (1H, t, J 10.8 Hz, HCHO E1), 3.87 (1H, t, J 11.1 Hz, HCHO E2) 2.66-2.71 (1H, m, H-2 E2), 2.03-2.14 (2H, m, H-3 E2 & H-2 E1), 1.48 (1H, dd, J 7.9, 11.5 Hz, H-3 E1), 1.41 (1H, dt, J 4.0, 8.0 Hz, H-3 E1), 0.87 (1H, dd, J 4.1, 11.3 Hz, H-3 E2).

Example 9

Preparation of a polymeric catalyst

20 A solution of dichlorobenzylidene-(N,N-bismesitylimidazolinylidene) tricyclohexyl-phosphine-ruthenium (II) (7.4 mg, 0.0087 mmol) in CH₂Cl₂ (2 ml) was *added via a cannula* to a solution of 7-oxa-2-norborn-2-en-5-ylmethyl 2-isopropoxy-3-ethenyl-phenyl ether (25 mg, 0.087 mmol from Example 7) and 7-oxa-2-norborn-2-en-5-ylmethyl benzoate (60 mg, 0.261 mmol from Example 8) in CH₂Cl₂ (3 ml) in a 5 ml round-bottomed flask under a nitrogen atmosphere and with vigorous stirring. After 25 10 min, the ¹H NMR analysis of the red reaction solution showed the complete conversion of the reactants, recognizable by the disappearance of the olefinic norbornene signals at 6.2-6.5 ppm. After adding CuCl (1 mg, 0.101 mmol), the resulting solution was heated to reflux for one hour, resulting in a pale green 30 solution.

After cooling, the reaction solution was concentrated under reduced pressure to dryness and the residue was taken up in a 1:1 mixture of hexane and CH_2Cl_2 . The insoluble copper salts were removed by filtration through a Pasteur pipette filled with 5 cotton wool.

The clear, green solution was concentrated to dryness under reduced pressure and the solid residue was washed successively with hexane (10 ml) and diethyl ether (10 ml). After drying under high vacuum, the polymeric product (74.5 mg, 93% of theory) 10 was obtained as a pale green, adhesive solid. The catalyst loading of the polymeric product can be determined by integration of the ^1H NMR signals at 16.67 and 7.99 ppm.

15 δ_{H} (500 MHz, CDCl_3): 16.67 (1H, bs, $\text{Ru}=\text{CH}$), 7.99 (60H, bs, *o*-Ar ester), 7.50 (31H, bs), 7.38 (62H, bs), 7.04 (18H, bs), 6.91 (9H bs), 6.74 (9H, bs), 5.7-5.6 (90H, bs) 5.21 (10H, bs), 4.7-3.7 (180H, m), 2.78 (20H, bs), 2.37 (61H, bs), 2.01 (50H, bs) 1.23 (60H, bs);

20 N.B.: the overlapping and very broad signals cause some integrals of the high-field signals to become closer together, but nevertheless consistent for different polymer charges.

Examples 10-24

25 General procedure for carrying out metathesis catalysis using the polymeric catalyst from Example 9

30 The substrate (compounds 14 to 21) (0.12 mmol) CH_2Cl_2 (1.6 ml) was added at room temperature to a solution of the polymeric catalyst from Example 9 (1.2×10^{-3} mmol) in CH_2Cl_2 (1 ml) under a nitrogen atmosphere. The resulting pale green solution was

stirred until the substrate had been quantitatively converted according to the ^1H NMR spectrum or thin-layer chromatography. After the reaction, the catalyst can be removed as a green adhesive material from the catalytic reaction mixture by adding cold diethyl ether (7 ml). Alternatively, the addition of cold hexane or a diethyl ether-hexane mixture leads to the precipitation of the catalyst as a green solid. The products (compounds 22 to 29) could subsequently be obtained by filtering and removing the solvent.

10

The catalysis results are compiled in Tables 1 and 2.

Table 1: Activity of the polymeric catalyst from Example 9 in metathesis reactions.

Example	Substrate	Product / (reaction time)	Conversion (%)
10			
			22 (45)
			>98
11			
			23 (360)
			>98
12			
			24 (60)
			>98
13			
			25 (15)
			>98

Example	Substrate	Product / (reaction time)	Conversion (%)
14			>98
	18	26 (60)	
15			>98
	19	27 (30)	
16			>98
	20	28 (270)	
17			>98
	21	29 (70)	

Table 2: Recyclability of the polymeric catalyst from Example 9 in the ring-closing metathesis of toluenesulphonyl-N,N-diallylamide

Example	Cycle	Time (min)	Conversion (%)
18	1	60	>98
19	2	60	>98
20	3	60	>98
21	4	60	>98
22	5	60	>98
23	6	120	>98
24	7	240	>98